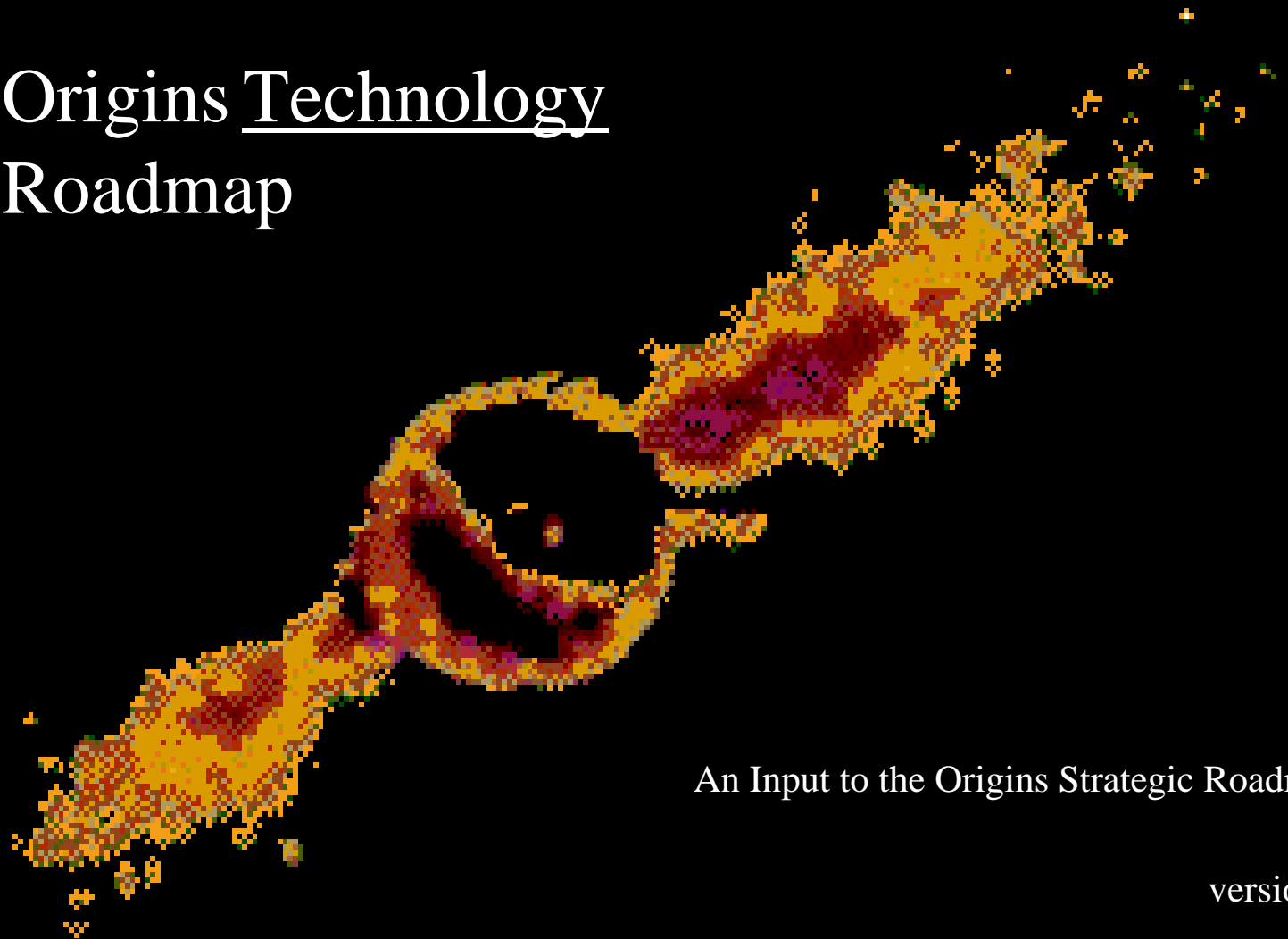


Origins Technology Roadmap



An Input to the Origins Strategic Roadmap

version 1

4/97

ORIGINS

This document is provided as an input to the Strategic Plan for the Astronomical Search for the Origins theme within NASA's Office of Space Science

Scope of the Roadmap

- *Even though Origins is a long range program, this technology roadmap concentrates on missions likely to be initiated within the next 10 years*
 - *Initial missions are based on significant improvements over the current state-of-the-art*
 - *Enabled by vigorous investment in technology for component development and system-level validation using both ground testbeds and flight demonstrations*
 - *Origins missions in the second decade of the new millennium will be even more capable scientifically, but based on more evolved technologies which are not directly addressed here*

The QuestionsThe Quests

- *Search for our earliest origins*
 - *What were the earliest structures produced within the Universe?*
 - *How did galaxies form?*
 - *How did primeval gas form the first stars?*
 - *Where and when were the heavy elements (C, N, O, ...) formed?*
- *Search for life beyond our solar system*
 - *How do stellar and planetary systems form and evolve?*
 - *What is the distribution and characteristics of planets around nearby stars?*
 - *How did the physical and chemical conditions necessary for life arise in the Universe?*
 - *Are there life-supporting planets orbiting nearby stars?*

Responding to the Science Quests

-- Missions within the Next Decade

- *Three new missions pave the way toward understanding our Origins*

Search for our earliest origins

- *Next Generation Space Telescope (NGST)*
 - *Large (4 - 8 m) Near IR telescope*

Search for life beyond our solar system

- *Two missions catalog the nearby planetary systems and search for Earth-like planets*
 - *Space Interferometry Mission (SIM)*
 - *Optical interferometer (10 m baseline)*
 - *Terrestrial Planet Finder (TPF)*
 - *Long-baseline (~100 m) infrared interferometer*

Assumed Launch Dates

- *Launch Dates will be determined by:*
 - *Recommendation of the science community*
 - *Technological readiness*
 - *Budgetary constraints*
- *For this document the assumed launch dates are*
 - *SIM* *2005 time-frame*
 - *NGST* *2007 time-frame?*
 - *TPF* *2010-2011 time-frame*

Observational Implications for NGST

- *Wavelength requirement: Near IR ($\sim 1\text{--}5^+ \mu\text{m}$)*
- *Spatial resolution requirement*
 - *0.05 arcsecond \Rightarrow requires 4-8 m aperture*
- *Sensitivity requirement*
 - *Taking spectra of small clumps of stars in early Universe ($z \geq 5$) \Rightarrow requires large collecting areas (4-8 m)*

Observational Implications for SIM

- *Search for planetary systems (around 15th magnitude star or brighter)*
 - *1 μ arcsec differential astrometry*
 - *Mission duration of 5+ years*
 - *To permit sufficient number of observations to have a significant fraction of planet's orbit*
 - *Wavelength near maximum brightness of stars: 0.4 - 1.0 μ m*
- *Calibration of age and distances in the Universe*
 - *4 μ arcsec global astrometry*
 - *Sensitivity for 20th mag. star: require 30 cm apertures*
- *Study of dynamics and evolutions of active galactic nuclei*
 - *Interferometric imaging*
 - *10 milliarcsec resolution: requires 10 meter baseline*

Observational Implications for TPF

- *Direct detection and characterization of exo-planets*
 - *Wavelength requirement: 7-17 μm*
 - *Band includes key molecular features*
 - *Spatial resolution requirement*
 - *0.02 arcsec imaging \Rightarrow require interferometers with ~ 100 m baseline*
 - *Starlight nulling requirement: 10^{-6}*
 - *Sensitivity requirement: **
 - *Detection of strongest atmospheric signatures (CO_2 , H_2O , O_3)*
 - *Require modest apertures: ~ 2 m with operation at 5 AU, or;*
 - *Require larger apertures: $\sim 4 - 6$ m with operation at 1 AU*
 - *Detection of weaker atmospheric signatures (CH_4)*
 - *Require larger apertures: $\sim 6^+ \text{ m}$ with operation at 1-5 AU*

**Strength and structure of exo-zodiacal emission is an important design constraint that requires better characterization for a final design.*

Complementary Missions

- *Within the Origins program ongoing space missions and ground facilities provide critical scientific and technological steps in advance of SIM, NGST and TPF*
 - *Hubble Space Telescope (HST)*
 - *Stratospheric Observatory for Infrared Astronomy (SOFIA)*
 - *Keck Interferometer*
 - *Space Infrared Telescope Facility (SIRTF)*

HST Contribution to NGST

- *Technological*
 - *Operational test-bed for near-IR detectors*
 - *Potential testbed for advanced optical techniques (Adaptive optics coronagraph for 2002)*
- *Scientific*
 - *Imaging and spectroscopy of star-forming regions, planetary debris disks, and distant galaxies*

SOFIA Contribution to NGST & TPF

- *Technological*
 - *Operational testbed for new IR detectors, arrays and instruments*
- *Scientific*
 - *Spectroscopy of star-forming regions*
 - *Analysis of the energy sources at the centers of galaxies*
 - *Determine elemental composition of galaxies in the local universe*

SIRTF Contribution to NGST & TPF

- *Technological*
 - *1 m-class light-weight cold optical materials*
 - *IR focal planes*
 - *Passive cooling of the entire observatory*
 - *Low-cost observatory mission operations*
- *Scientific*
 - *Characterization of exo-zodiacal dust clouds*
 - *Detection of high-z galaxies*

Keck Interferometer Contribution to SIM and TPF

- *Technological*
 - *Development of 85 m interferometer operating at 10 μm (hardware, software, observing techniques)*
 - *Development of nulling technology*
 - *Autonomous operation of interferometers*
- *Scientific*
 - *Characterization of exo-zodiacal dust clouds*
 - *Detection of large mass planets around nearby stars*

Technology Commonality Between SIM, NGST & TPF Missions

Modest amount between SIM and NGST

- *Large lightweight precision space structures*
- *Vibration isolation*
- *Precision deployments*

Substantial amount between SIM and TPF

- *Precision metrology*
- *Active control*
- *Space Interferometric system integration/test/operation*
- *Starlight Nulling*
- *Precision deployable structures*
- *Vibration isolation and suppression*

Substantial amount between NGST and TPF

- *IR operation,*
- *Large, cold optics*
- *Low noise, large format array detectors*
- *Passive cooling*
- *Cryo-coolers*

Guiding Principles for Technology Development

- *Invest early in high payoff technologies*
 - *Enable technical feasibility of implementing the missions for acceptable risk within cost caps*
- *Use ground testbeds*
 - *Use rapid prototyping of H/W and S/W and validate the design in the ground testbeds*
 - *Adjust requirements as needed to maintain “build-to-cost”*
- *Use flight demonstrations when needed to validate partial or full system designs and confirm ground testbed results*

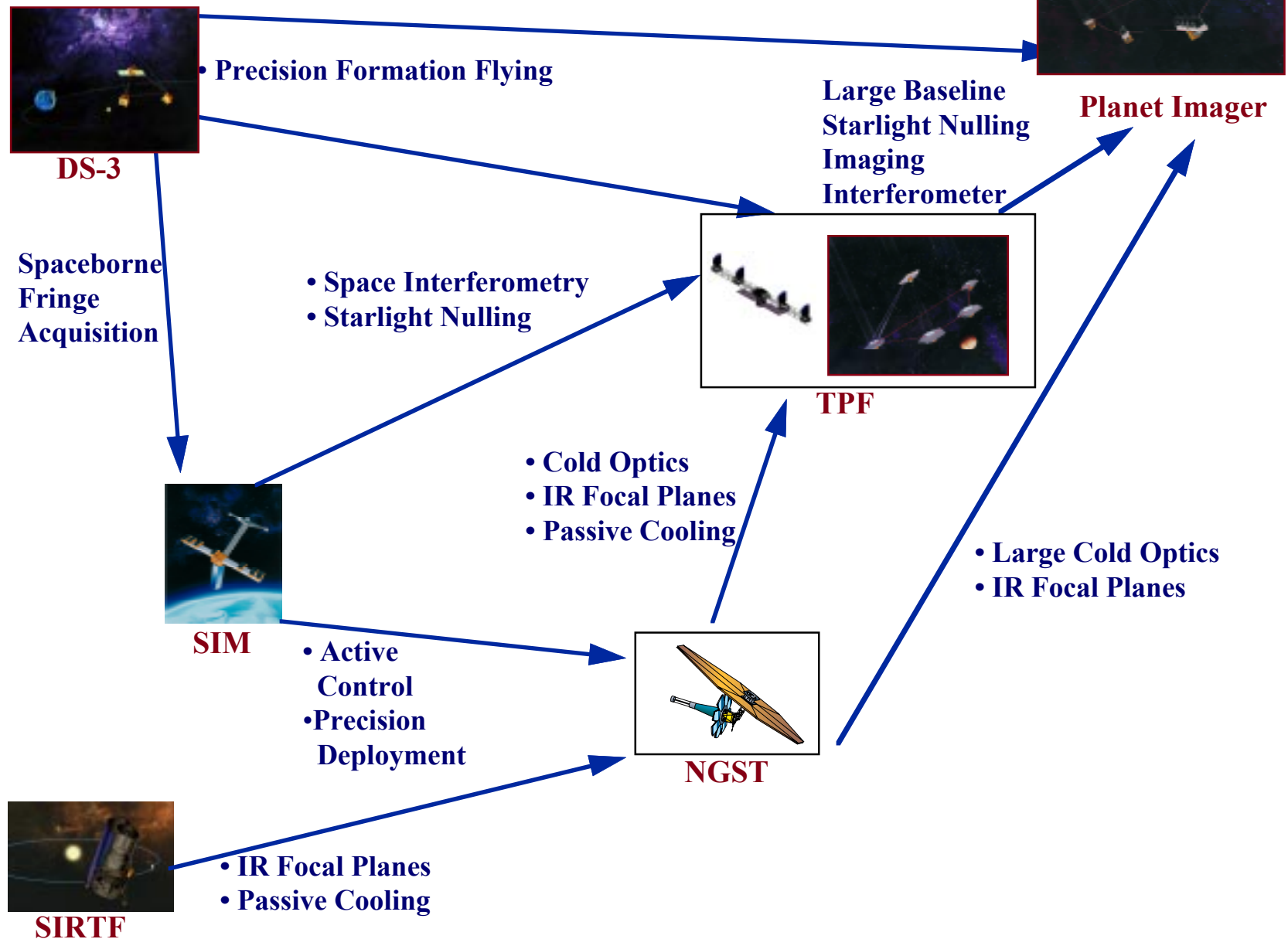
Guiding Principles for Technology Development (cont.)

- *Partner with other agencies (NRO, DOD, NSF) and other countries*
 - *Take advantage of their expertise*
 - *Leverage NASA funds*
- *Ensure effective use of industrial and academic expertise in each mission*
- *Use competition to ensure that the best ideas and most affordable designs emerge*

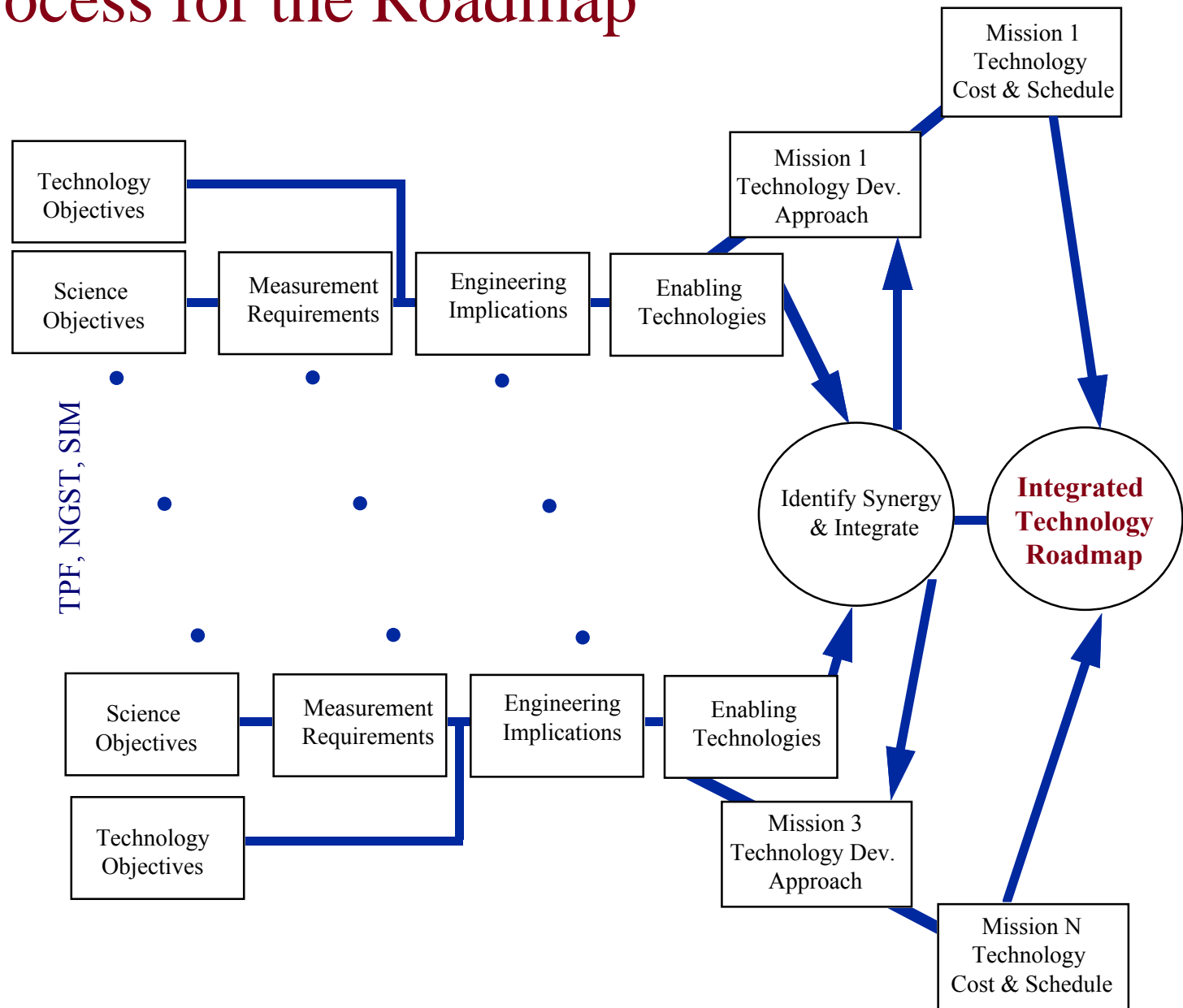
Missions as Pathfinders

- *Each mission within the Origins portfolio provides significant scientific contributions towards the Origins goal and, in addition, contributes technologically towards the next set of missions*
- *Design and architecture of each mission is thus affected by two drivers:*
 - *Mission's scientific objectives*
 - *Its role as a technological pathfinder for subsequent missions*

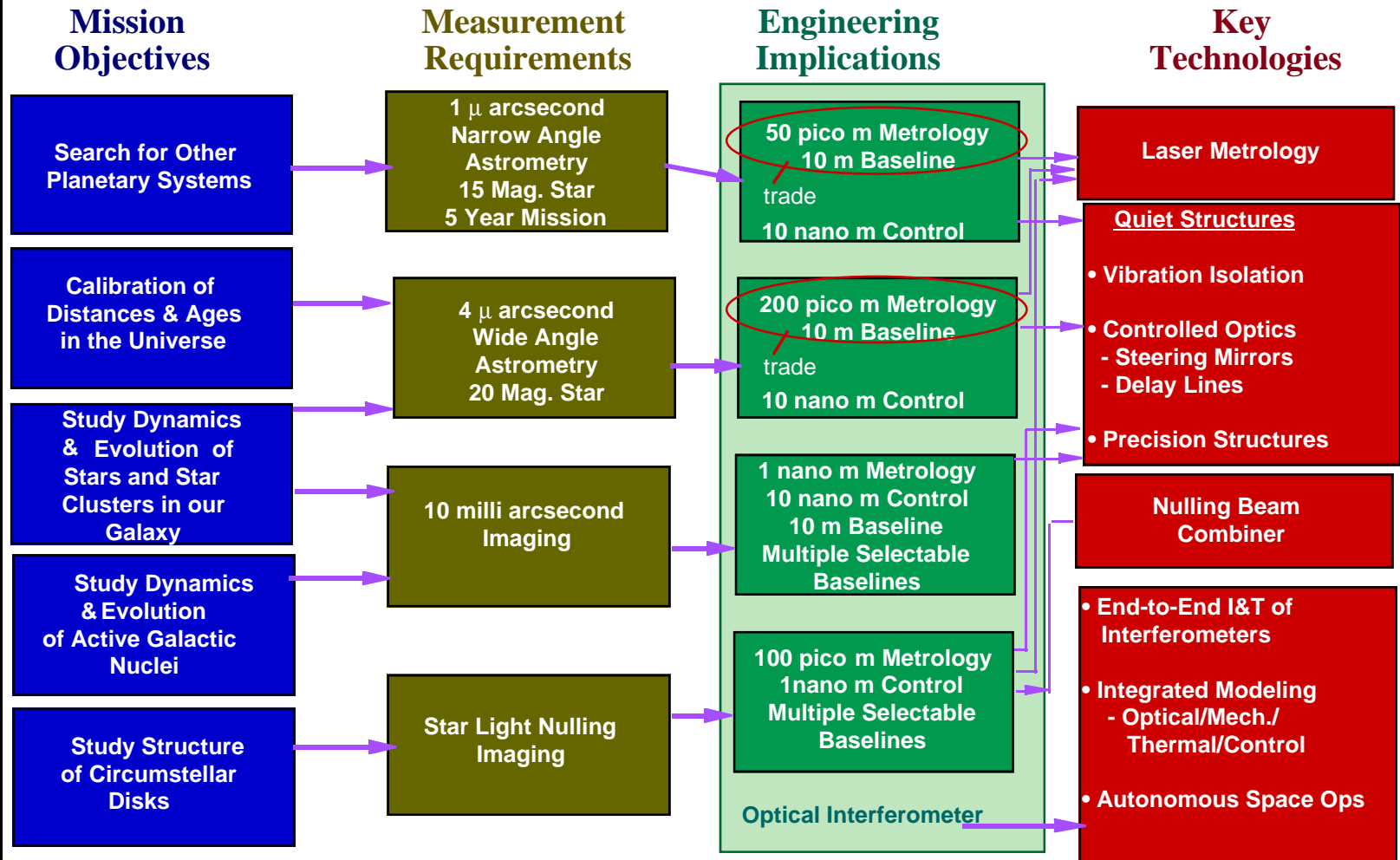
Origins Missions -- Technology Flow



Process for the Roadmap



SIM Requirement Flow Down



Key SIM Technologies

Quiet Structures

*Vibration Isolation
& Structural Quieting
(nanometers)*

*Precision Deployable
Structures
(millimeters)*

*Focal Plane Nulling
(10^{-4})*

Starlight Nulling

*Controlled Optics --
Steering Mirrors & Delay
Lines (nrad / nm)*



Metrology

*Laser Metrology
(picometers)*

*End-to-End
Integration & Test
of Interferometers*

*Integrated Modeling
Optical/Mechanical/
Thermal/Control*

Interferometer I&T

SIM Technology Development Approach

Components

- *Develop interferometer hardware component technology*
 - *Transition component capability to industry via competitive procurements and SBIR Focused Topic in Interferometry*
- *Develop and prototype mission critical software*
 - *Real time code for autonomous on-orbit operation*
 - *Ground software for science data processing*
 - *Integrated modeling software for on-orbit performance prediction*
- *Use early rapid prototyping of H/W and S/W to validate the technology in a number of ground testbeds*
 - *Allow components to interact in a system environment*
 - *Shake down the requirements*

SIM Technology Development Approach System

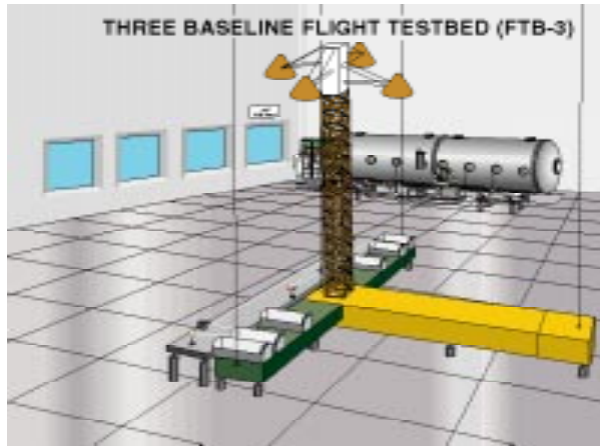
Ground Testbeds

- *Develop ground testbeds for use through out the project life*
 - *Microarcsecond Metrology (MAM) Testbed*
 - *SIM System Testbed (SSTB)*
 - *Palomar Testbed Interferometer (PTI)*

Flight Test

- *Validate technology in space where necessary*
 - *Microdynamics of precision deployable structures*
- *Use New Millennium Program DS-3 mission to detect fringes in space*

SIM System Ground Testbeds



SIM System Testbed (SSTB- 3)

- Nanometer active control on flexible str.
- Full scale
- Full complexity -- form; fit and function
- Three baselines



Micro Arcsecond Metrology (MAM) Testbed

- Picometer metrology
- 1/5 Scale
- Operation in Vacuum
- Three baselines



Palomar Testbed Interferometer (PTI)

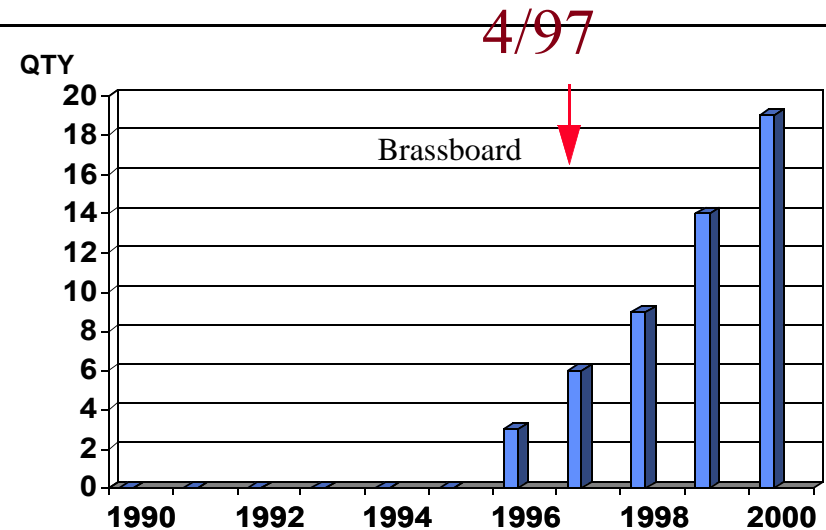
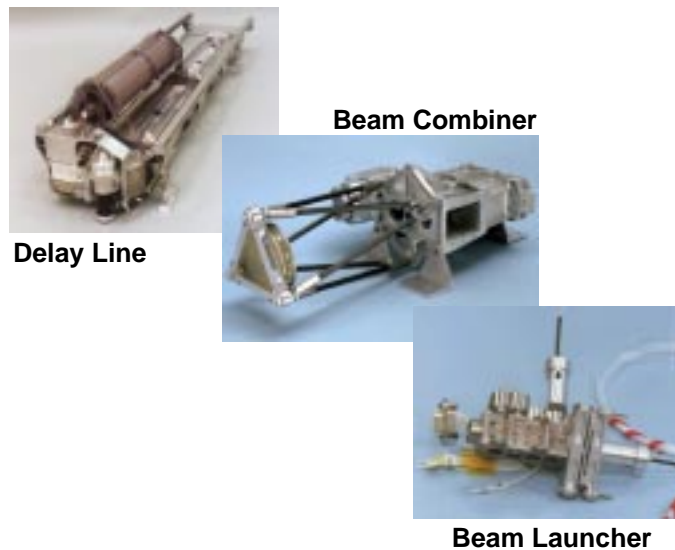
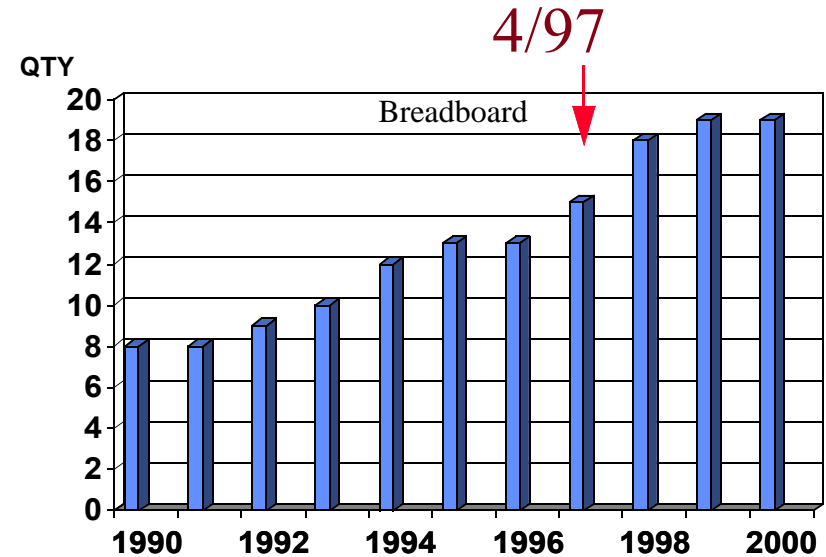
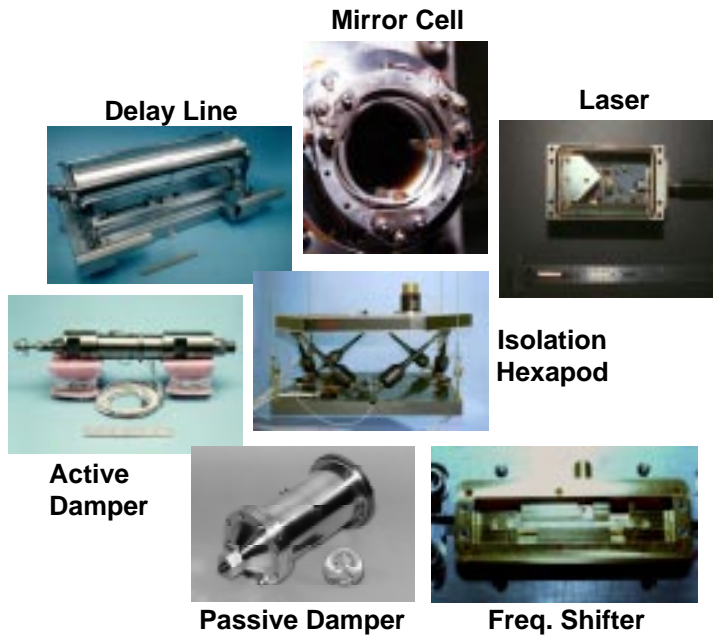
- Fully functioning 110 m baseline interferometer
- Science data processing

SIM Technology Readiness

Progress Metrics

- *How mature is the interferometer component hardware?*
 - *Percentage of breadboards and brassboards finished*
- *How mature is the interferometer control software?*
 - *Percentage of software modules designed & prototyped*
 - *Prior S/W available for reuse (with upgrades)*
- *Are the demanding performance specifications within reach?*
 - *Nanometers of optical path difference stability*
 - *Picometers of sensed optical fiducial position*
- *To what extent has the component hardware and software been integrated and tested in relevant test environments?*
 - *Status of system level ground testbeds*
 - *Status of flight demonstrations*

Critical H/W Component Maturity

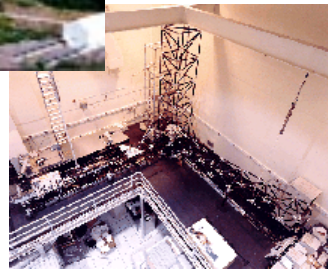


Software Development Flow/Reuse



Palomar
Testbed

SIM System
Testbed
Version 1



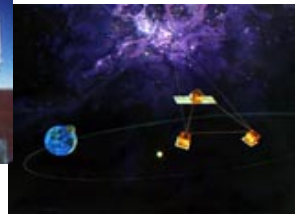
Microarcsecond
Metrology



SIM System Testbed
Version 3



Keck Observatory



DS-3

• *Past relevant S/W Developments*

- Developed a total of 184 S/W modules, (90,000 Lines Of Codes -- LOC), for operation of Palomar Interferometer Testbed
- Utilized 138 of the above S/W modules, (63,000 LOC), and developed 31 additional modules, (22,000 LOC), to bring Version 1 of SIM System Testbed on line

• *Testbeds S/W Developments*

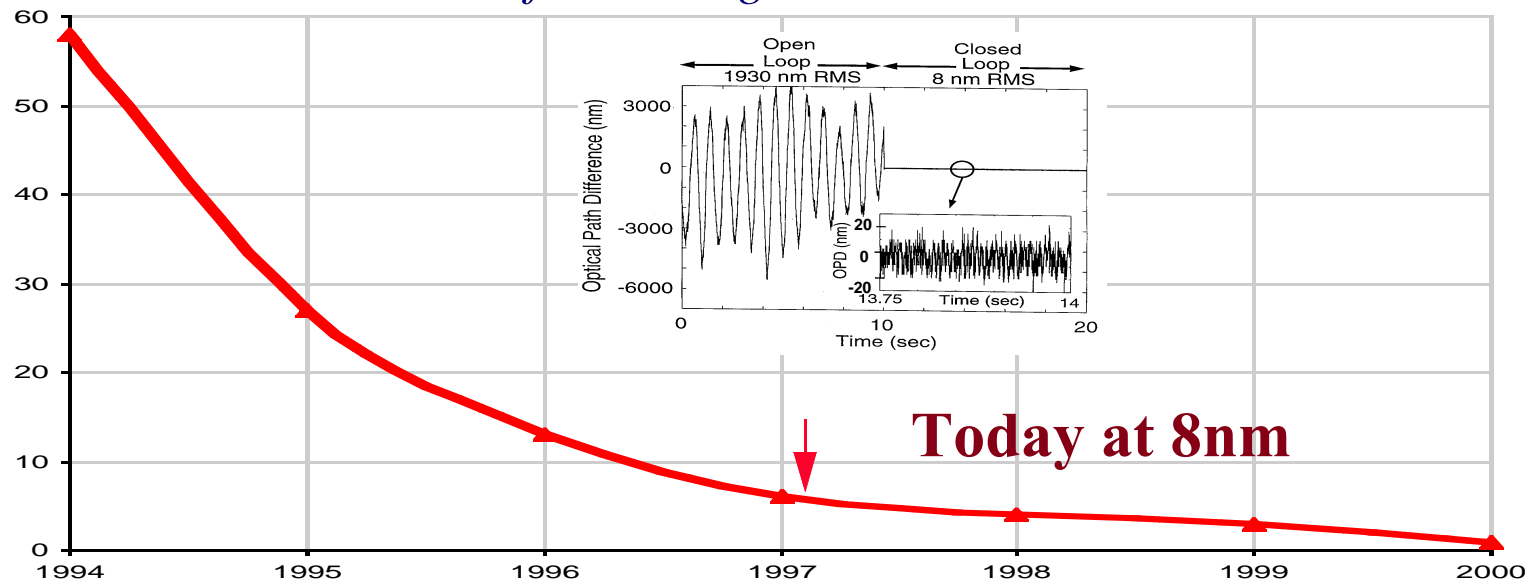
- Ground testbeds will need 61 modules (70,000 LOC). To Date 15 modules, 6,500 LOC have been written, tested, and documented. These are upgrade of the codes written for Palomar and SSTB-1
- Keck and DS-3 will use this S/W for the Interferometer Operation with minimal upgrades

• *SIM S/W Developments*

- SIM Flight S/W will use the above S/W foundation with reuse and upgrades as necessary

Progress in Nanometer Stabilization

- *Requirements:*
 - 10 Nanometer for Astrometry
 - 1 Nanometer for Nulling



SIM System Testbed Version 1



SIM System Testbed Version 3

Picometer Spatial Metrology

OBJECTIVE

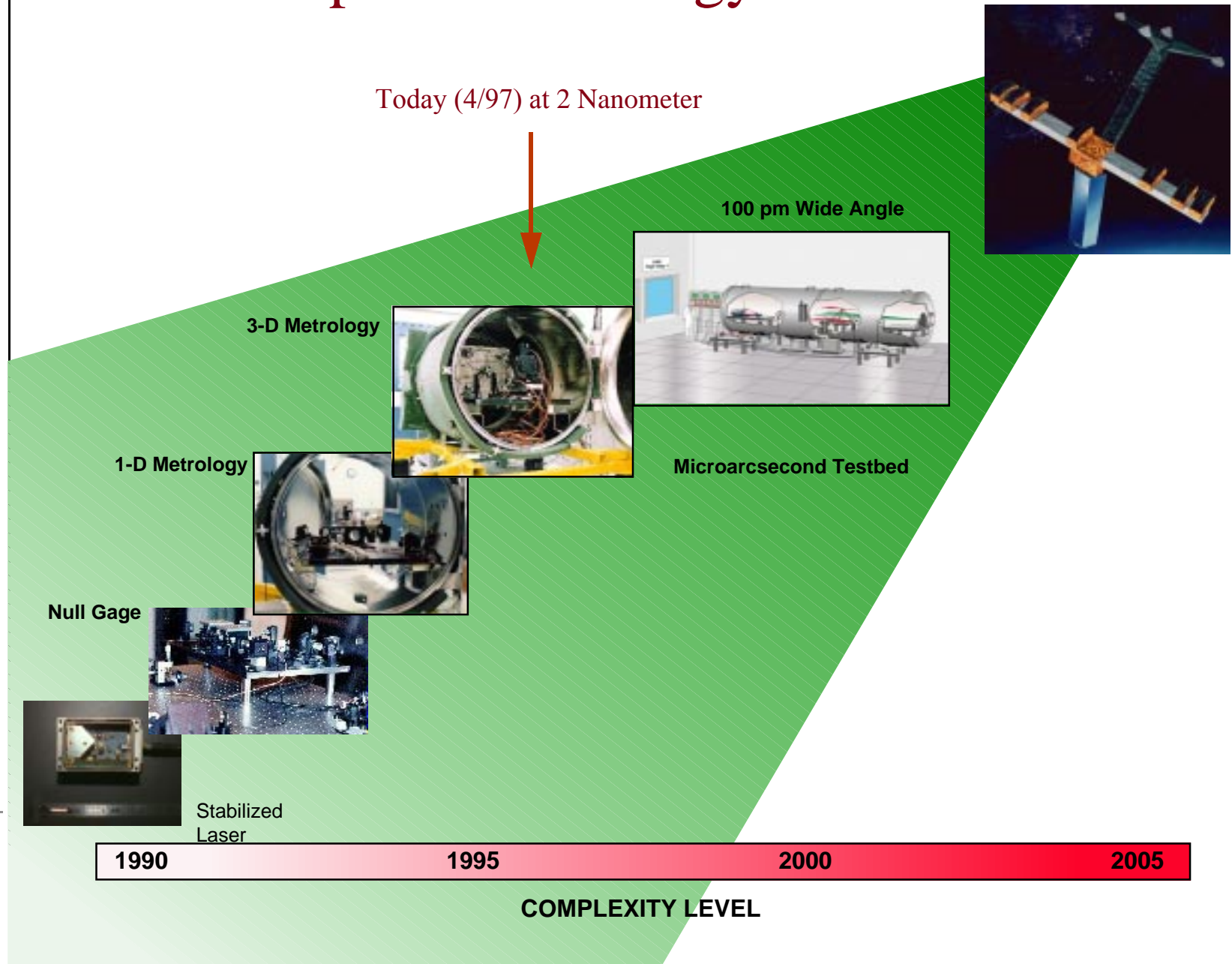
- *Demonstrate the capability to measure the relative orientations of 3 collinear interferometer baselines to 100 picometers in 3-D*
 - *Orientation of each baseline is determined from 3-D position of a pair of corner cubes at each end of the baseline*

APPROACH

- *Develop a stabilized laser -- the “yardstick”*
- *Demonstrate picometer level measurements in 1-dimension*
- *Demonstrate that a set of 1-D laser gauges can be configured into an “optical truss” to make 3-dimensional 100 picometer level measurements*
 - *Initially-- track 1 corner cube with 5 relative gauges (3-D metrology experiment)*
 - *Ultimately -- track 6 corner cubes with 21 relative gauges (Microarcsecond Metrology Testbed)*

ORIGINS

Picometer Spatial Metrology



SIM Technology Flight Experiments

- *A series of modest flight tests requiring the unique attributes of the space environment will be flown*
 - *Interferometer Program Experiments (IPEX 1&2)*
 - *IPEX-1 -- Characterize micro-g vibration environment of German Astro-SPAS platform (flew on STS-80 -- 12/96)*
 - *IPEX-2 -- Fly representative deployable structure on Astro-SPAS & measure microdynamic response on-orbit (manifested for 7/97 launch)*
- *The New Millennium Program Deep Space -3 mission is planned to be a separated spacecraft interferometer flying before SIM CDR*
 - *Will use many of the same H/W comp. and S/W modules as SIM*
 - *Will build confidence in the ability to integrate, test, launch, and operate a space based optical interferometer to obtain fringes*

Interferometry Integration and Test

- The same Interferometry Team would have built, tested, and operated 7 interferometers prior to SIM



**Mt. Wilson
Interferometer**



Palomar Testbed



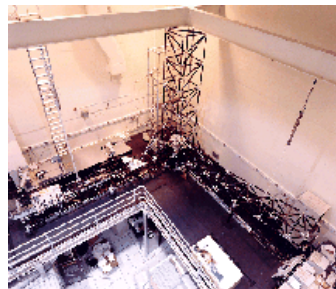
**Microarcsecond
Metrology**



**SIM System
Testbed**



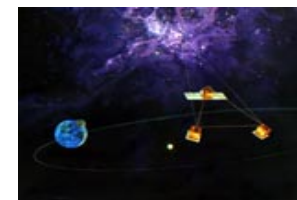
SIM



**SIM System Testbed
Version 1**



Keck



DS-3



SIM Development Flow

COMPONENTS



GROUND TESTBEDS



FLIGHT EXPERIMENTS

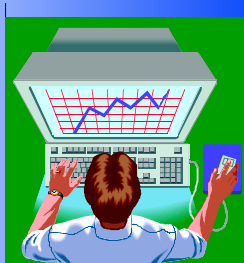
DS-3



IPEX



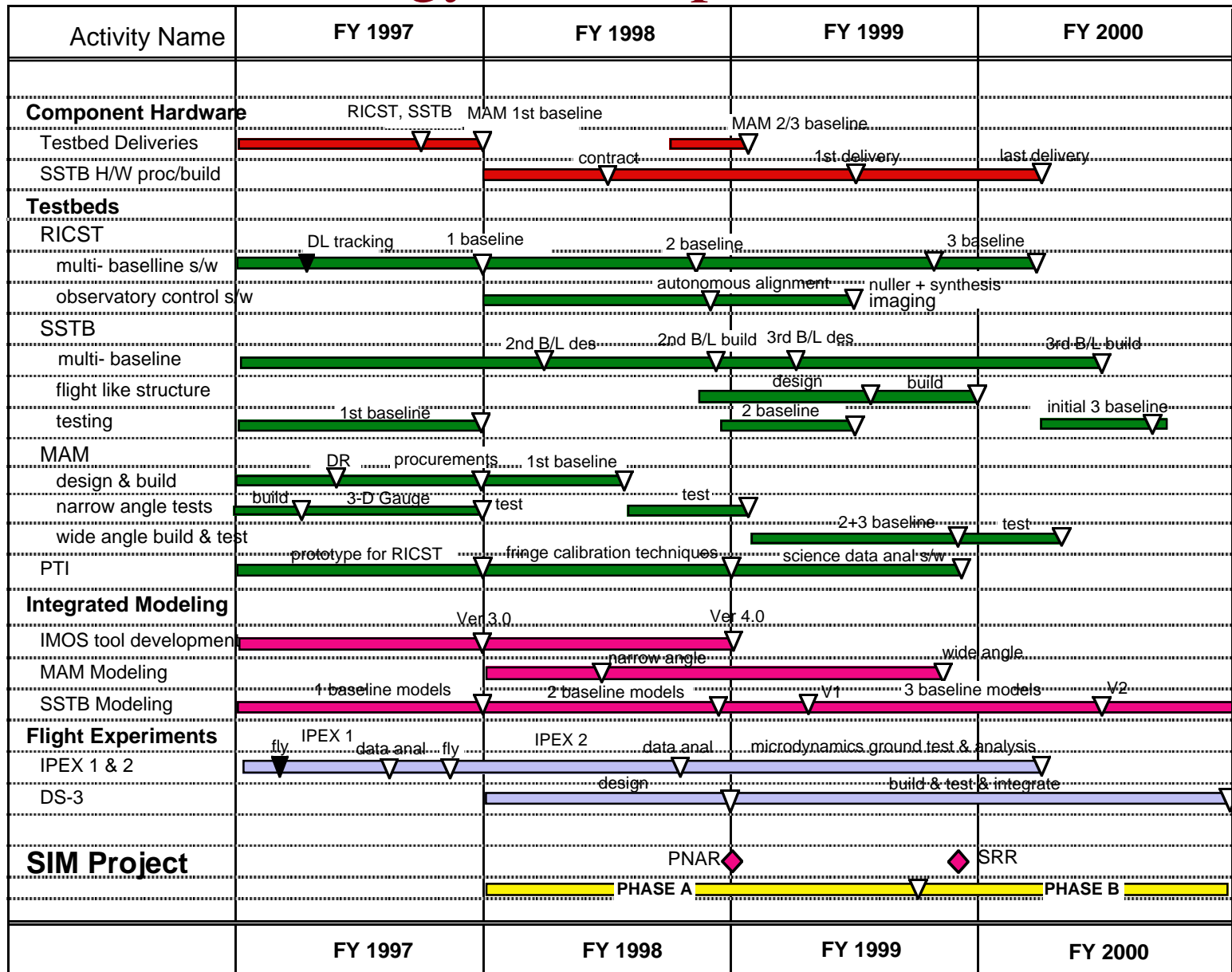
ELECTRONICS & S/W



PALOMAR TESTBED



SIM Technology Development Schedule



NGST Science and Technology Drivers & Engineering Implication

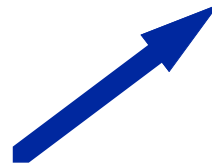
Scientific Drivers

- *See galaxy formation and evolution with high resolution at high z*
 - *Find and monitor earliest supernovae*
 - *Find earliest globular clusters*
 - *Compare distant and foreground galaxies*



Measurement Requirements

- Imaging and spectroscopy at 0.5 - 20+ μm , optimized over 1 - 5 μm
- 0.05 arcsecond resolution at 2 μm
- nano-Jansky sensitivity
- $\geq 3 \times 3$ arcminute field of view



Technological Driver

- Pathfinder to future large aperture space telescopes and interferometers



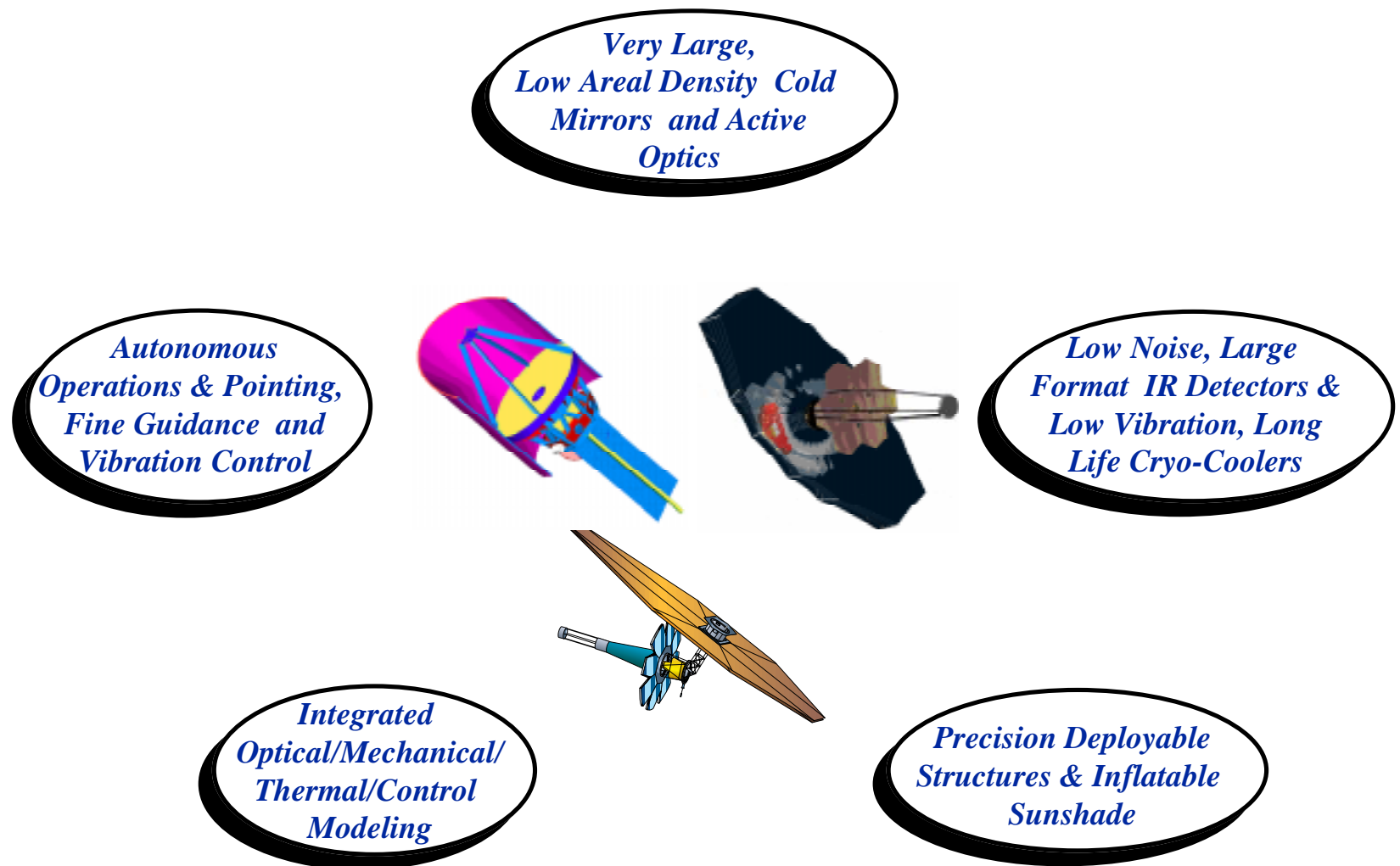
Engineering Implication

- 4+ m diameter aperture near IR telescope
- Passive cooling to $<50\text{K}$
 - Large sunshield
- Orbit at L2, 3 AU or above the ecliptic
- Wide field cameras
- Multi-object spectrograph
- Wide field visible/IR detectors
- Low noise near IR (1-5 μm) detectors
- Low noise thermal IR (5-20 μm) detectors
- Zodiacal limited detector sensitivity
- 5 year lifetime (10 year goal)



Enabling Technology

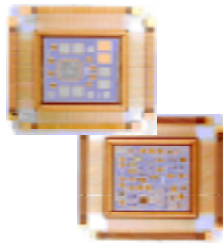
Key NGST Technologies



NGST Technology Development Approach

- *Develop advanced component/subsystem technology via competitive procurements to industry, academia & national laboratories/observatories*
 - *Lightweight Mirror Demonstrator System RFO*
 - *IR detectors and cold actuator NRAs*
 - *Science instrument development grants*
 - *Industry directed technology development RFPs/grants*
 - *SBIR grants in various areas*
- *Leverage off existing NASA Technology programs*
 - *Interferometry Technology Program*
 - *Cryo-coolers*
 - *Inflatable structures*
 - *New Millennium Program*
- *Validate technology in ground-based breadboards and testbeds*
 - *Primary Mirror Test Facilities, Precision Deployable Structures Testbeds, Wavefront Sensing/Control Testbed, Telescope System Testbed, Science Instrument Testbeds, Operations Testbed, Flight System Testbed*
- *Perform flight validation of key technologies where necessary to achieve relevant environmental conditions*
 - *inflatable sunshade experiment*
 - *gravity release experiments*
 - *deployable optics flight experiment*

Selected NGST Component/Subsystem Technology Development



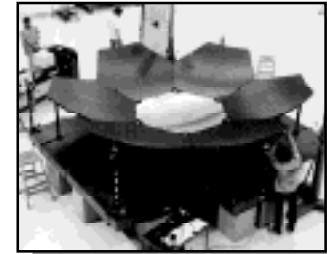
**Large Format
Low Noise IR Arrays**



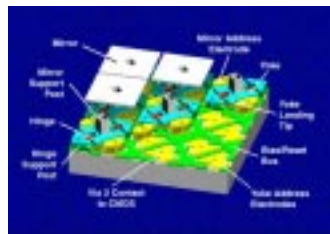
H₂ Sorption Cooler



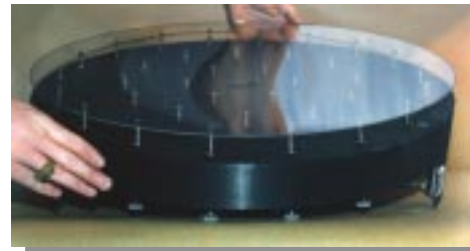
Turbo Brayton Cooler



Deployable Structures



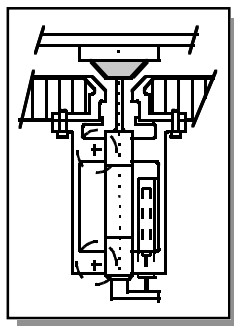
Digital Mirror Array



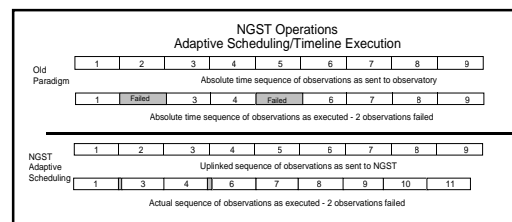
Lightweight Active Mirror



**Rigidizable Inflatable
Structures**



Cold Actuators

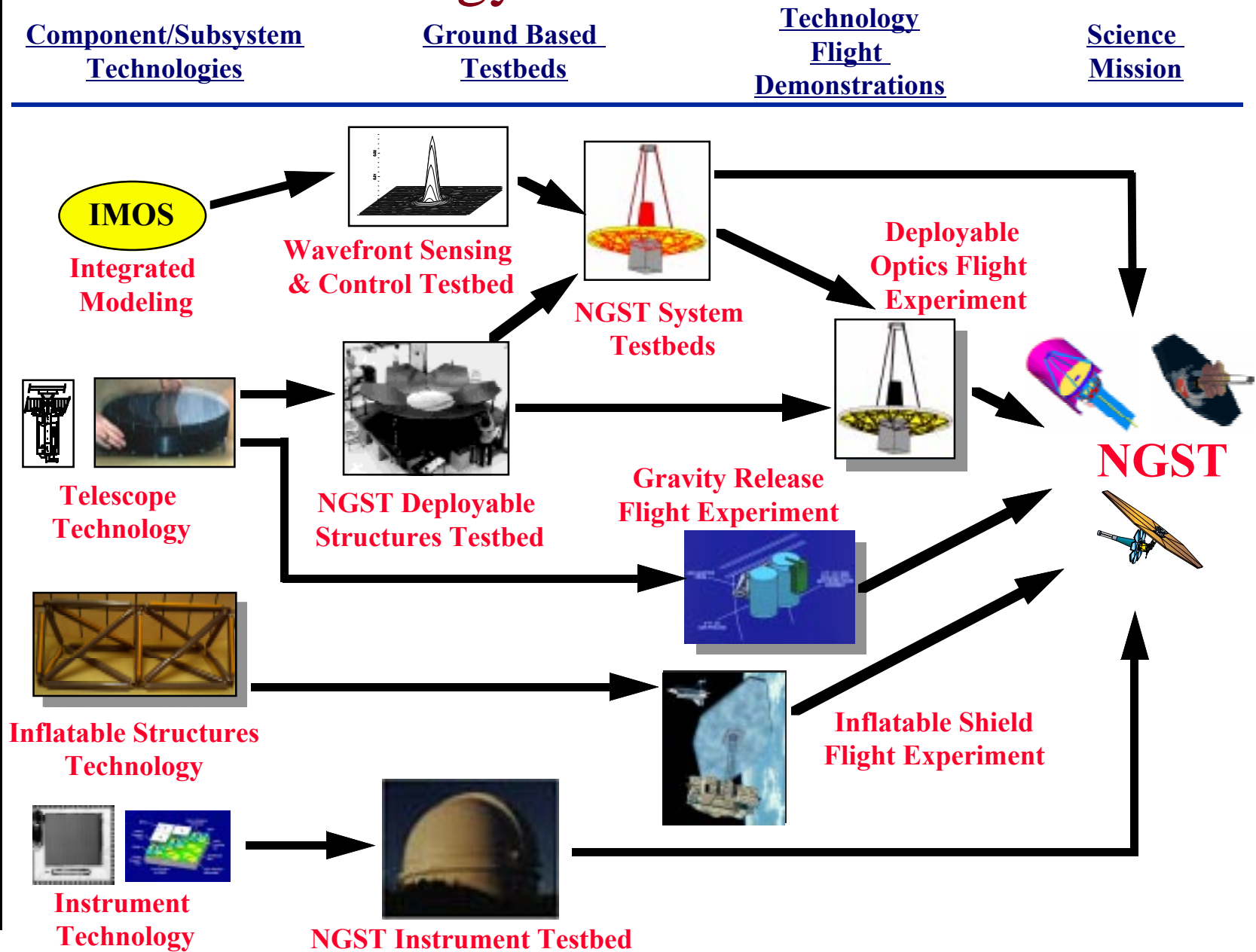


**Operations Technology
-Adaptive Scheduling**



Active Vibration Isolator

NGST Technology Flow



NGST Flight Experiments

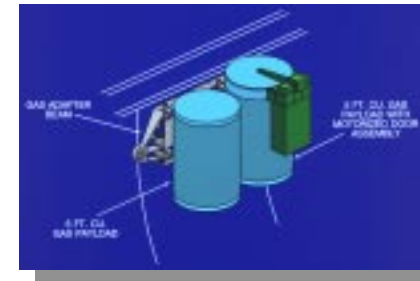
Pathfinder 1- Inflatable Shield In Space Experiment

- Demonstrate feasibility of using inflatable technology to passively cool NGST optical systems
- Collect thermal and dynamics data both during deployment and on orbit
- Shuttle based free-flyer in 2000



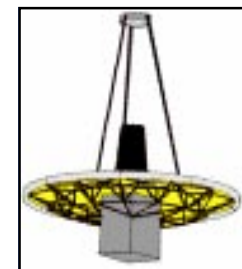
Pathfinder 2- Gravity Release Flight Experiment

- Demonstrate effects of zero gravity on lightweight mirror and deployment mechanisms
- Collect figure data on mirror and stability data on deployment mechanisms
- Gas Can and HitchHiker Experiments on Shuttle in 2000

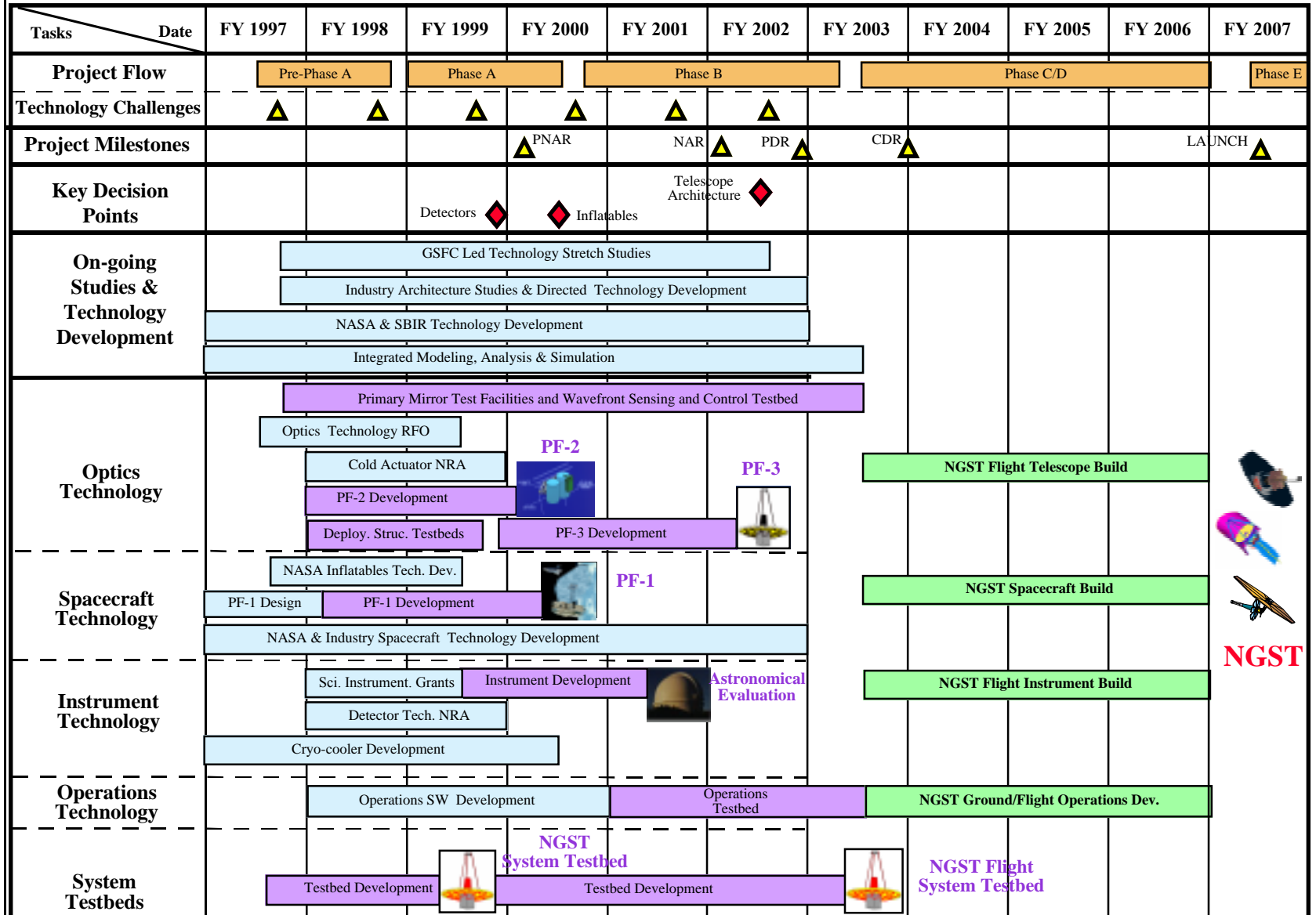


Pathfinder 3- Deployable Optics Flight Experiment

- Demonstrate precision deployment
- Collect deployment, alignment, phasing, and optical control and dynamics data
- Shuttle based free-flyer in 2002



NGST Technology Development Schedule



TPF Science Drivers & Engineering Implication

Scientific Drivers

- Identification & characterization of Earth-mass planets around nearby stars
- IR spectroscopy of planetary atmospheres outside the solar system
 - Strong signatures: potential for life support
 - Weak signatures: potential detection of life
- High spatial resolution imaging of astrophysical sources

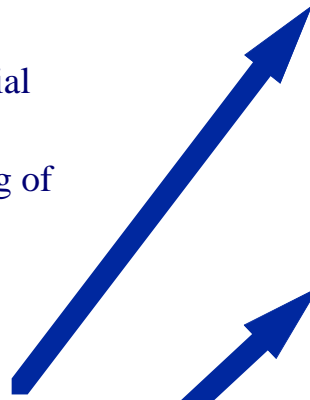


Measurement Requirements

- 10 milliarcsec imaging
- Operate from 7 - 17 μm
- 10^{-6} starlight nulling
- Broad uv-plane coverage for imaging

Other Factors

- Structure & density of exo-zodi



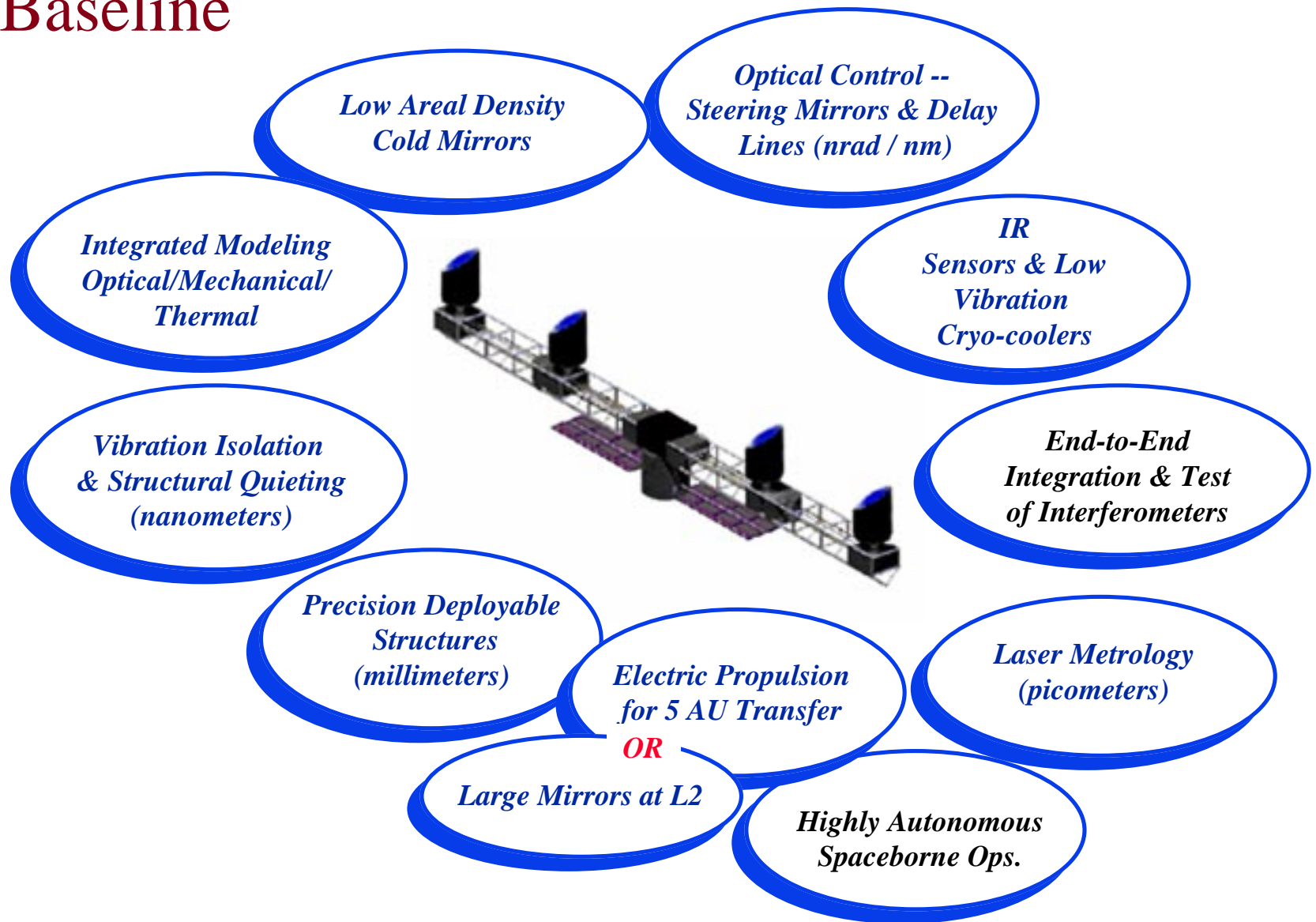
Engineering Implication

- 50 - 100 meter deployments, initial placement and long term stability -- millimeters OR precision constellation formation flying -- centimeters
- 1.5 - 6 meter apertures depending on orbit
 - Orbit at L2 or 3 -5 AU
- Passive cooling to $< 40\text{K}$
- Cold operation of:
 - Structural stabilization - nanometers
 - Precision spatial knowledge -- picometers
 - Precision pointing control -- nanoradians
- Precision pathlength control -- nanometers
- Ability to model, with picometer accuracy, interactions of mechanical, optical, thermal, and control systems
- Very low noise focal plane arrays

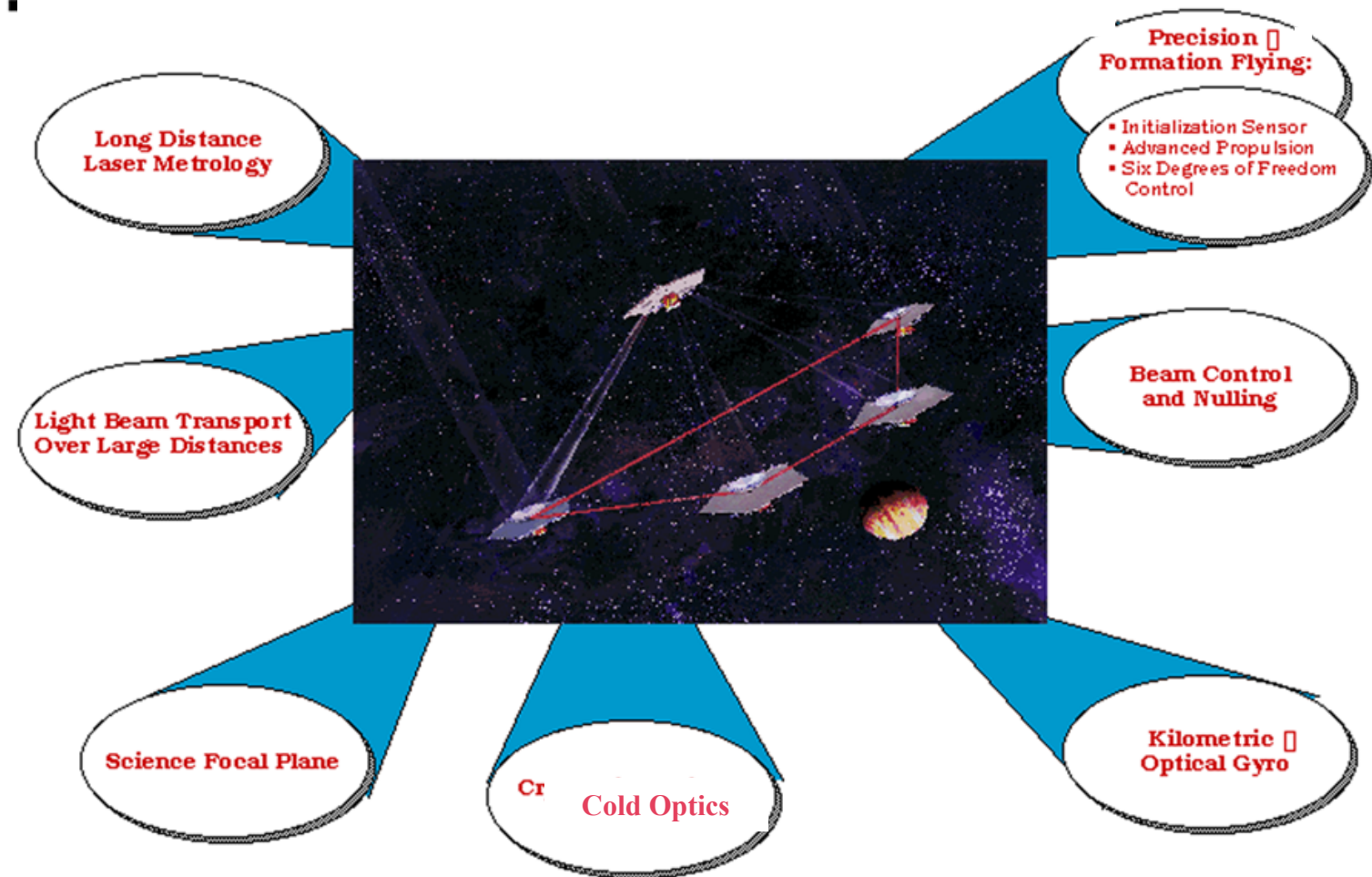


Enabling Technologies

Key TPF Technologies -- Physical Baseline



Key TPF Technologies -- Virtual Baseline



Near-Term Activities on TPF

- *Design dependent on characteristics of both local and exo-zodiacal clouds' structure and intensity. More information will become available through*
 - *NRAs for theoretical studies*
 - *Keck Interferometer*
 - *SIRTF*
 - *SIM*
- *Industry-led parametric architectural studies are planned to identify sensitivities and knees in technology and cost curves for physical vs. virtual baseline (separated S/C)*
- *TPF will also benefit substantially from earlier Origins Technology development/missions*
 - *SIM will pathfind space interferometry technologies*
 - *NGST technology investments on cold optics and IR detectors (as well as large deployable optics if needed) will benefit TPF*
- *If formation flight technology is needed, either dedicated precursor flights or flights of opportunities will be pursued*
- *Nulling in the lab and at Keck*